

## **Intelligent Mobile Systems for Assembly, Maintenance and Operations for Space Solar Power**

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NASA has been commissioned to investigate the feasibility of an orbiting Space Solar Power system that is capable of generating power from space and transmitting the power to earth based rectennas. The structures for these systems would be large (1 km and greater) that would require robotic assembly, maintenance and operations. The robotic and autonomous operations required for the space solar power structure can be divided into three main areas: 1) initial assembly of the transmitter array and the photovoltaic power subsystem, 2) inspection of the assembled structure to determine that the assembly process has been correctly conducted and continued inspection of the system to evaluate its integrity and functionality, 3) Maintenance and repair of transmitter elements or tiles and the photovoltaic power subsystem.

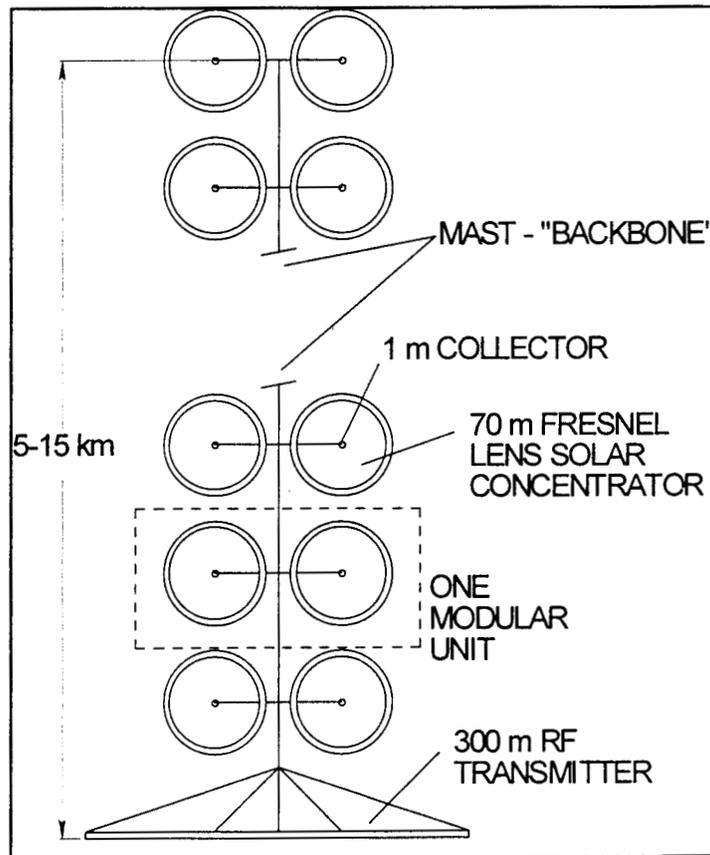
Due to the number of operations and differences in the required operations, no single robotic system will suffice. For example, the assembly activities required for the transmitter tiles will be dictated by the transmitter design. There will be the need for an OMV free flyer activity to bring the transmitter tile to the growing transmitter array, acceptance of the tile by an autonomous robotic system and then the positioning and placement of the tile into the growing array. There will be a need for multiple robots, each defined for a specific function (e.g. assembly vs. maintenance). Also there may be the need for the robotic systems to be Reconfigurable to adapt to the specific task. The ability to reconfigure should be limited to the changing of end effector. This ability to reconfigure would reduce the number and type of robotic systems. The nature of the robotic systems will also be dictated by the location of activity. Mobility on and around the structure will be a primary requirement. This paper will discuss design options, and the technology development needs for the Space Solar Power system, after a brief introduction to some of the basic system configurations.

### **System Configurations**

Feingold, et. al. (1) completed a concept definition study systems study in 1998 for Space Solar Power. One conclusion of that study was that GEO based sun towers provided advantages over LEO or MEO based systems. GEO-based SSP systems, in

general, hold many advantages over power satellites in other orbits. Their 24-hour power delivery can provide sufficient baseload power for many of the markets being considered without the need for significant investment in ground energy storage. Minimal electronic beam-steering can distribute or time-share power as needed to many different ground sites. Furthermore, the smaller beam-steering angles required at GEO permits larger transmitter element size/spacing for easier dissipation of waste-heat. Most importantly, GEO provides the most benign radiation environment of the orbits considered for SSP. The current planning is to have a series of interim developments, each of increasing power. The initial system would be a 150 KW, going through stages to 10 MW with the potential for a 1 GW system. For the 10 MW and larger systems, several architectures have been conceived and are under study. One basic concept that shows all of the system components is the Sun Tower architecture. Other variations have multiple backbones or have a ring (1). Concepts are still evolving. The Sun Tower is presented as being illustrated of the system components.

The sun tower concept is described as a long structure(possibly 5-15 km for the GW class architectures), which is defined as the backbone for the solar collectors and houses the cable bus for delivering the collected energy to the transmitter. The entire sun tower would be a gravity-stabilized satellite oriented somewhat normal to the Earth's surface. It would be placed in a geosynchronous orbit. One concept is to have the collectors as a series of 50-70 m diameter fresnel lens focusing the solar energy onto a 1 m diameter photovoltaic array. The figure illustrates a simple sketch of this system. These lenses would be supported in space by an expandable, possibly inflatable structure with the 1 m collector held in space by another astro-mast type structure. Other concepts for the solar power generation include high efficiency multiple-band-gap photovoltaics, deployed as flat



planar structures. The basic unit for the photovoltaic power generation will be a series of modular units that contain either a single or paired photovoltaic panel/collector system, connected to the mast backbone, which would in turn contain power management and distribution (PMAD) cabling and associated insulation. It is expected that these modular units will be self contained and will autonomously deploy. The robotic activities

associated with the power generation side of the system are limited to transferring the modular units to the growing structure with an orbiting maneuvering vehicle (OMV), docking the units with the growing structure, and initiating the self-deployment process. After assembly, there would be a robotic inspection and maintenance.

On the earth-facing side of the structure, there is the RF transmitter. This structure is expected to be up to 300 m in diameter. The transmitter itself would be an FET-based device comprised of a phased-array RF transmitter capable of beaming 5 GW or more of energy to Earth or another spacecraft/satellite. The phased-array would be composed of a series of 2 meter RF panels, possibly, but not necessarily, square in shape. Each of these tiles would be individually assembled in to the growing transmitter array. Other geometry's have been considered for the transmitter panel, including a hexagon or triangular structure. The final geometric shape would be based upon packing efficiencies and ease of assembly. The transmitter tiles would be .15 to .3 meters thick, and would contain all of the electronic hardware. There will probably be a need for a supporting back structure, which could range from .2 to .8 meters in depth. The alignment specification requires all of the RF tiles to be placed with less than a 1 mm gap in the x-y plane, but the surface RMS can vary in the z axis such that there is less than 10% surface distortion from the center line. This structural stiffness requirement translates to an alignment tolerance in the z axis of 1-5 mm. It is this system that has the greatest challenges for autonomous robotic assembly.

#### Required Robotic and Autonomous Systems Technology Development Issues:

The nature of the robotic systems will also be dictated by the location of activity. Mobility on and around the structure will be a primary requirement. For activities in the vicinity of the mast, a track rider system or a multiple legged walker (N-pod) may be the preferred means of locomotion. For motion around the transmitter array, either a free flyer or an gantry type system could accomplish the required mobility. Each system has specific advantages and disadvantages, and the selection of the best system would be based on the overall system and structural architecture.

The structural architecture will both define and limit the robotic activities. If there are either a track or positioning grappling hand holds, then a structure based robotic system can be utilized. If the structure cannot be directly grappled, then a free flyer system must be used. This raises the issue of whether the deployed structures can act as a support, and whether they have sufficient structural stiffness that mobility of the robotic systems on the structure will not create any disturbance rejection concerns or affect the control for structural dynamics. It is preferred that as many deployment activities be conducted autonomously or by a predetermined self-assembly function. This is the baseline for the photovoltaic power modules. Robotic assembly would be utilized when there is not a straight forward mechanical solution. The architecture will also define issues such as the ability to repair or to replace elements. It is expected that transmitter tiles will have to be replaced during the life of the SSP system, but it may be advantageous to either deactivate or remove from service photovoltaic arrays that either fail or are disabled. In this scenario, the arrays are either left in place or jettisoned, and a

new replacement array is added at the end of the tether. This has significant system issues for the PMAD subsystem, but conducting this type operations would have a lower risk of failure or additional damage than trying to add a photovoltaic array in the middle of the mast structure. All of these system trades will have to take into account the size and scalability of the system.

The SSP autonomous and robotic functions would be built upon a set of core technologies. For the robotic assembly of the solar array structure and for the transmitter phased array, the core technologies are:

- stereo vision/3D perception
- pattern/object recognition
- constrained linear motion (tracks)
- unconstrained motion (walking)
- free flight motion with or without tether
- force sensing and control
- simple grappling
- complex manipulation
- inertial moment compensation
- sensing
- manipulation feedback
- state estimation/monitoring
- robotic motion planning/visualization
- structural damping/force compensation

The core technical development objectives for the autonomous assembly of the solar array structure are to have a system that includes a robust stereo vision and pattern recognition system of structural elements or markers in representative lighting. The lighting is a specific concern for a spaced system, since one cannot expect uniform lighting on a large three dimensional structure. There is the need for constrained local robotic motion and operations on the mast backbone, as well as unconstrained motion on a larger scale on the SSP backbone between adjacent or nearby modules. There will be the need to have force sensing and regulation of structural elements to prevent any dynamic interactions. All of these actions will require both simple and complex grappling of structural elements.

The technical development objectives for the robotic and autonomous assembly of the transmitter array is to develop an systems approach that allows for continuous capability growth as the diameter of the array increases. This will be by the combination of robotic system, intelligent mechanisms, and mechanically cooperative parts. A specific challenge for the assembly of the of the transmitter array is to develop a system that functions on both the front and back. Access from the rear may be constrained by the transmitter substructure and cabling. Access from the front may be limited by the inability to touch or grapple the transmitter tiles. Because of these limitations, it is expected that a cooperative scheme between two different types of robots will be required to conduct the array assembly and any subsequent maintenance. Possible systems would be a gantry robot which is anchored to points along the array external ring structure that accepts and places the transmitter tiles with a free flyer that brings in the transmitter tiles from a storage location. It is expected that there will be mobile or robotic arms either attached to the truss structure or to the gantry robot to conduct the fine manipulation for placement and alignment.

Robotic Inspection/Maintenance of the SSP system will involve cooperative interaction of multiple robots having varying levels of autonomy, intelligence and capability. Robots may be either single function, multifunctional or reconfigurable in nature. The best approach is to develop a new class of *n-pod walkers & track riders*, or free flyers having multifunctional tools and the manipulation capability to visualize, inspect, conduct NDE, and provide repairs and maintenance of electrical/structural elements.

### **Current SSP Robotics Development at JPL**

The current robotics development at JPL is focused on developing a prototype robotic system that is capable of assembly, inspection and maintenance operations on a SSP structure. Its primary application would be for operations involved within the back structure of the transmitter array, and on the PMAD backbone. Because of these constants, the system must be relatively small, agile and capable. The system that is being developed is named LEMUR for Legged Excursion Mechanical Utility Robot. The baseline concept is shown in Figure 2. This is a six-legged walking robotic system with autonomous operation capability. Its primary features are a mechanical mobility and manipulation subsystem, autonomous computing and navigation subsystem and software development and power subsystems.

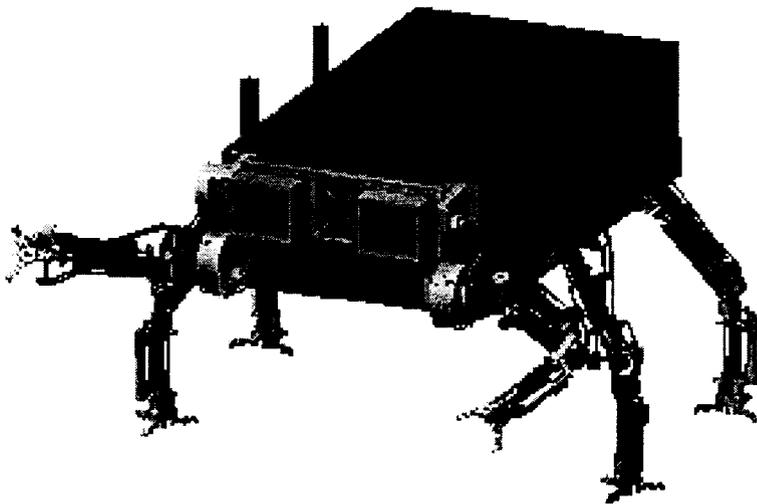


Figure 2: Legged Excursion Mechanical Utility Robot (LEMUR) baseline

The mechanical subsystem consists of a lightweight graphite composite chassis with the six independently operated legs. The basis for the structural design is the JPL Sample Return Rover described in Reference 2. The rear four legs will have 3 DOF and the front two with 4 DOF. The front two legs should be reconfigurable to allow the integration of a mechanical tools. The kinematics will be such that it can support itself on the four rear legs, and preferably on three. The left front leg will have a grapple hand with an in-line macroscopic imager. This is illustrated in figure 3. This small grapple hand will be capable of simple and complex grapple. When it is fully opened it will have a 2 inch open diameter and passive grip adjustment. It will be capable of gripping spheres, cylinders or irregular objects. Built into the hand will be integrated

contact sensor. The right front leg will have rotary mechanical tool . This is illustrated in Figure 4. The mechanical tool will be retractable and reversible rotary tool integrated into lower half of the leg. It will have a contact sensor for placement and an integrated electro-mechanical clutch mechanism to prevent over-torque.

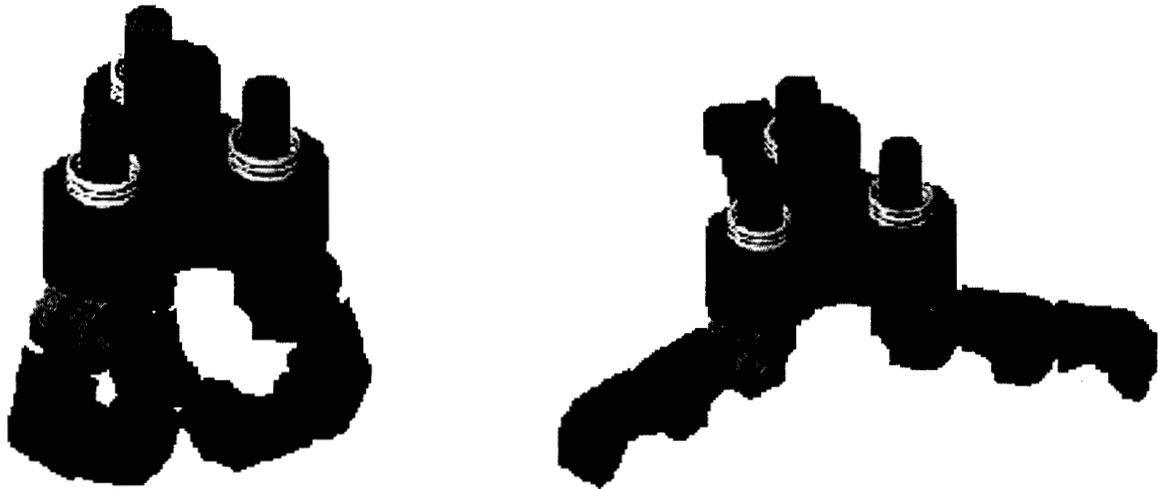


Figure 3: Miniature Grappling foot concept that is being integrated into the left front foot of LEMUR in closed and open positions.



Figure 4: Mechanical Rotary Tool is being integrated into the right front foot of LEMUR

The computing and navigation system is based on a PC 104 architecture. This architecture has been utilized for previous technology rovers at JPL and is described in Reference 2. The navigation system consists of a stereo pair of cameras that is used for navigation for 1-10 meter traverses and hazard detection and obstacle avoidance maneuvers. A tactile pressure sensor on each of the legs to acknowledge that it has touched the ground. A full inertial navigational system consisting of three single-axis accelerometers also mounted in a triaxial arrangement. The inertial system provides knowledge of the rover pitch, roll, yaw, distance traveled, speed, and acceleration. Included in the computing and navigation system is a color frame grabber for storing

images, and a modem for communication and remote operation. The closed-loop position and velocity control of all actuators is accomplished via microcomputer control using optical encoder feedback from each actuator. The motor control signals are generated by the D/A converter and multiplexed through a sample/hold circuit located on the D/A multiplexer board. The multiplexed outputs are sent to a series of custom-built PWM amplifier circuits that provide the control voltage to each motor

The LEMUR robotic system is currently in fabrication, with completion scheduled for fall 1999. The current plan is to conduct a simulated operation scenario by the end of 1999 that demonstrates the ability to be commanded to move along a defined path that is representative of a truss structure. All commands will be via a wireless modem. Once the system is within 1 meters of the location, it should have the ability to acquire a visual image of a mechanical assembly, and proceed towards it under autonomous control. Once LEMUR is at the mechanical assembly, it will conduct a simple mechanical operations with both of the front mechanical tools. The system should then be capable of transmitting series of visual images back to a host computer.

### **Summary**

The Space Solar Power technology program requires innovative and challenging robotic systems for assembly, maintenance and operations. A multitude of robotic systems will be needed to conduct the assembly, maintenance and operations. To meet some of the challenges, a new class of reconfigurable, walking robotic system called LEMUR is being developed to meet some of the potential robotic operations that will be required. This system will be capable of autonomous operation, traverses under stereo navigation control and mechanical manipulation. Two new mechanical tools are being developed for integration into the walking legs: a miniature grapppling hand and a retractable mechanical rotary tool. This prototype system is in development and will be demonstrated Fall 1999.

### **Acknowledgement**

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